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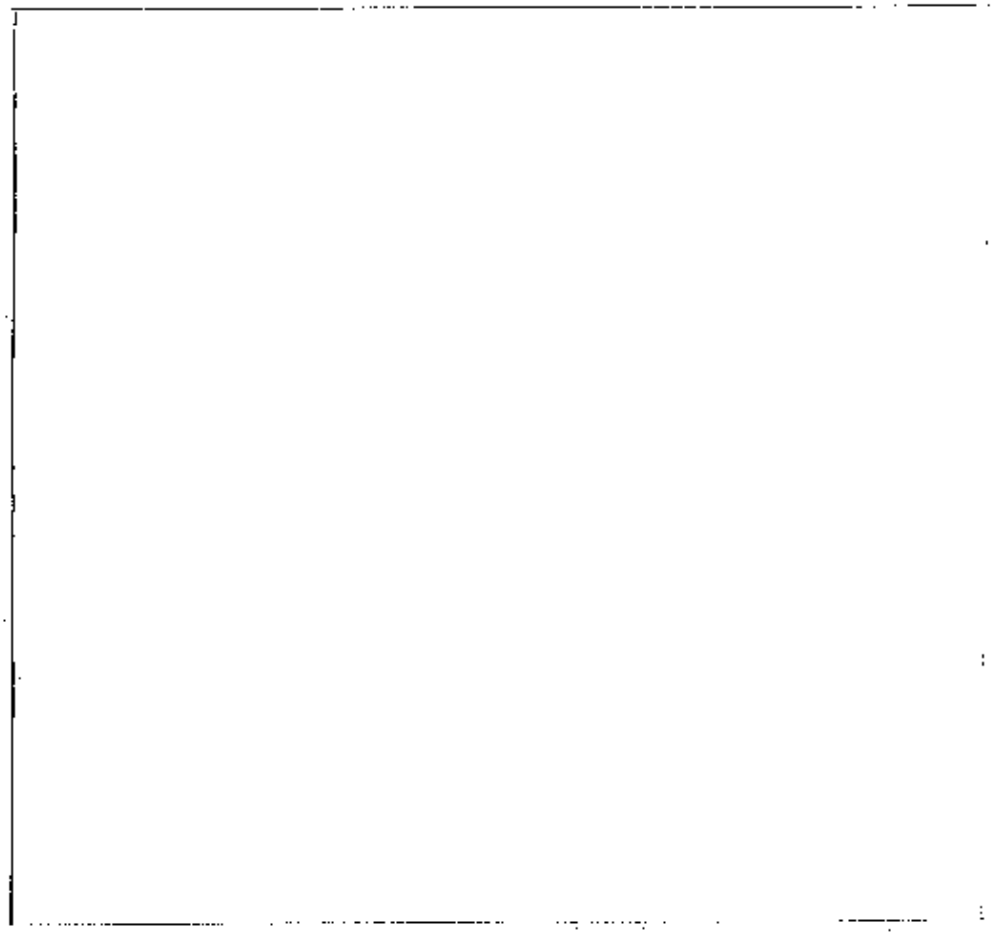

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WHAT IS BIODIVERSITY WORTH TO A DEVELOPING COUNTRY? CAPTURING THE PHARMACEUTICAL VALUE OF SPECIES INFORMATION

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WHAT IS BIODIVERSITY WORTH TO A DEVELOPING COUNTRY? CAPTURING THE PHARMACEUTICAL VALUE OF SPECIES INFORMATION

1. Introduction[1]

There is currently a resurgence of interest in the use of biodiversity as a source of novel chemical compounds for the development of new pharmaceuticals. A growing number of pharmaceutical companies are initiating or upgrading research programs that screen microbial sources, higher plants and other taxonomic groups for useful activity against disease targets. On the supply side developing country governments, development agencies and non-governmental organizations are increasingly interested in assisting developing country institutions to *capture* the 'pharmaceutical value' of biodiversity.

However, there are some potential misunderstandings in the view that pharmaceutical prospecting can serve as a mechanism by developing countries to extract *compensation* for conservation of their biodiversity. In an effort to clarify the pharmaceutical value of biodiversity and species information, this paper investigates the economic relationships involved in pharmaceutical prospecting.[2] The paper argues that an over-emphasis on the question of *how to capture the value of biodiversity* misses the key development question - that of *how to invest in the generation of information about biodiversity*.

The divergence of views on this subject comes from the failure to draw a clear distinction between biodiversity as the 'raw material' in the production process and information about biodiversity - the 'intellectual property' that drives innovation. As a raw material, biodiversity is typically treated as a *free good*. As a consequence, pharmaceutical prospecting provides little in the way of financial incentives for a developing country to invest in biodiversity protection. On the other hand, the ability to patent novel chemical compounds does provide an incentive to generate information about species that is useful in producing new and marketable drugs. The economic link between biodiversity and pharmaceuticals is the development of information about species and their chemical constituents.

The paper suggests that in order to capture the pharmaceutical value of biodiversity, developing countries would need to come up with a practical mechanism for controlling access to the country's biodiversity. Through the effective implementation of their sovereignty over national biological resources, developing countries could establish their

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[1]This paper draws heavily on research undertaken for an ongoing LEEC research project entitled 'The Economic Value of Species Information and its Role in Biodiversity Conservation: Case Studies of Costa Rica's National Biodiversity Institute and Pharmaceutical Prospecting.' The study is supported by the Swedish International Development Authority and conducted in cooperation with Costa Rica's National Biodiversity Institute and the Tropical Science Center. We are grateful to comments by Josh Bishop, Jo Burgess and David Simpson on earlier versions of this paper.

[2]'Pharmaceutical prospecting' is defined as the process of deriving marketable pharmaceuticals from natural products.

ability to derive just compensation (or payment) from the market for biodiversity samples. An alternative means of establishing a fair share of the returns from the raw material is to move into information-generating activities that add value to the resource itself. Generating species information in-country may be a more practical means of capturing the pharmaceutical value of biodiversity. In addition, such investment enables the country to appropriate a larger share of value added in the drug development process.

To illustrate some of these issues, the paper develops a theoretical model of the investment choices that face a developing country as it begins the process of deriving new drugs from natural products in the tropics. The model distinguishes between the investment, or 'effort,' devoted to the *in situ* protection of biodiversity and the 'effort' involved in generating information through expending effort on species classification and conducting research into the pharmaceutical properties of natural products. The 'effort' involved in producing one is generally divisible from the 'effort' involved in producing the other. Thus, developing countries face two investment objectives: (i) investing in protection of biodiversity and (ii) expanding their ability to produce species information. By indicating the likely relative returns to these two types of 'effort' the paper demonstrates that investments in protection and information generation are complementary activities and should be considered in tandem if a country is to achieve an optimal mix of the human and biological resources at its disposal.

2. Pharmaceutical Prospecting as an Economic Activity

Novel chemical compounds with marketable potential as prescription drugs are currently derived either from natural sources or by chemical synthesis in the laboratory. Historically, however, all medicinal preparations were derived directly from nature. Since the 1800s interest in the research and development (R&D) of natural product-based pharmaceuticals has been of a cyclical nature as synthetic chemistry and, more recently, efforts at 'rational' drug design based on knowledge of biomolecular processes have lead researchers to 'abandon' the use of natural products. In the past few years, new technological developments - including advances in receptor and mechanism-based screening technology - have rekindled the interest of pharmaceutical companies in the exploration of plants, marine organisms, microbial sources and insects for novel chemical compounds.[3]

Farnsworth and Morris (1976) point out that although 'guesstimates' can be made about the untapped potential of biodiversity, it is practically impossible to actually determine when a particular species has been fully investigated for its pharmaceutical properties. For example, Douros and Suffness (1980) report that in the first natural products screening program by the National Cancer Institute (NCI), 35,000 species of plants were screened for anti-cancer activity. In other words, in the most extensive pharmacological investigation of plants ever recorded, only a fraction of the total number of plant species

[3]See Findeisen and Laird (1991), and Mallinckrodt and Laird (1992) for an update on pharmaceutical companies engaged in pharmaceutical prospecting. Also, note that industry *has* shown a sustained interest in microbial diversity as a source of new leads.

were evaluated for a single type of activity (Farnsworth and Morris 1976). In addition, these plants were only tested against a particular set of cancer screens. In its new program initiated in 1986, NCI is testing natural products against a revised set of disease-oriented screens (Suffness, Newman and Snader 1989). Hence, it is possible to conclude that due to improvements in NCI's screening technology the original 35,000 species of plants are once again 'uninvestigated' sources of anticancer compounds.

Improvements in screening technology and the development of new screens clearly 'extends' the potential applications of the chemical diversity resident in natural products. New screens are a response not only to scientific and technological advances in isolating disease targets, but to the continued evolution of diseases. Increasing levels of disease resistance to commonly-used drugs is of particular concern in the case of tuberculosis, pneumonia, meningitis and other infectious diseases. The scourge of new and evolving diseases affects both the developed and the developing world. AIDS is a global epidemic, while resistance to traditional malarial drugs plagues the tropics. In the United States, population shifts to outer-edge suburbs and rural areas combined with increasing deer and tick populations have lead to increasing dangers from Lyme disease (U.S. News and World Report 1992).

Thus the sheer scale of the resource - on the order of 10 to 100 million species - and the continuing evolution of screens, screening technologies and disease targets implies that biodiversity will never be fully explored or exploited for its pharmaceutical potential. This suggests that the chemical properties of biodiversity represent a potentially limitless (relative to demand) renewable resource 'pool' for use in the development of new pharmaceuticals. The real threat to this resource is on the supply side - the competing uses of land and natural habitat and the failure to protect areas rich in biodiversity, particularly in the developing world.[4]

'Pharmaceutical prospecting' - the process of generating new pharmaceuticals from natural products - begins with biodiversity and ends with the production of a marketable drug. There are a number of activities in this process, including:

- the protection of biodiversity
- the collection and identification of biotic samples
- the extraction and screening of biotic samples
- the isolation and structural determination of lead compounds
- additional pre-clinical research including laboratory and animal testing
- clinical research and
- development of mass-production techniques for marketable compounds.

Pharmaceutical prospecting does not necessarily proceed in a linear, stepwise fashion as outlined above. However, the process generally involves adding information to the 'raw material' of biodiversity and its subsequent forms.

[4]See Swanson and Barbier (1992) for an overview of the potential role of biodiversity in economic development and the factors contributing to the loss of biodiversity.

In economic terms pharmaceutical prospecting activities can be segregated according to three major types of investment:

i) investment in protection of biodiversity
ii) investment in collection and identification of biotic samples and
iii) investment in pharmaceutical R&D.

The economic outputs of these investments are

- the 'raw material' for pharmaceutical prospecting - biodiversity
- species information and the 'processed product' - biotic samples and
- information about a species' pharmaceutical properties and the 'final product' - a marketable compound.

In the remainder of the paper we focus on the principle economic ingredients of pharmaceutical prospecting - *biodiversity* and *species information.*

3. Capturing the Value of Pharmaceutical Prospecting

An initial analysis of the economic characteristics of biodiversity and species information reveals obstacles that impede society's ability to obtain an 'optimal' level of investment in the production of these goods. We then discuss evolving and potential market and policy solutions to these *incentive* problems which may assist developing countries in capturing the value of pharmaceutical prospecting.

The Protection of Biodiversity

The protection, or maintenance, of biodiversity must be included in an economic analysis of pharmaceutical prospecting because the supply of this 'raw material' input involves a significant social cost. The social costs of protecting biodiversity are the direct costs of protection and the opportunity cost of allocating land to the production of biodiversity. As economically profitable alternative land uses may exist for lands currently functioning as reservoirs of tropical biodiversity, it is important that the production of biodiversity be capable of generating real economic benefits. Otherwise, there is little economic incentive for society to protect biodiversity.

The use of the 'raw material' input in pharmaceutical prospecting may involve three different interventions at the level of the biological resource itself:

- initial collection for identification to the species level
- further collection for further research and development and
- 'mass' collection or cultivation if a marketable drug results.[5]

[5]This is necessary if commercial synthesis of the compound is not feasible. Balandrin *et al.* (1985) suggest that since most natural product leads are secondary metabolites from a technical perspective they will be difficult - and therefore costly - to synthesize.

Depending on the case, only the first or second collections may be required or all three interventions may be necessary. Collection of microbial species in the form of a single environmental sample typically yields enough 'starter' material for researchers to develop methods for culturing species that show promise in early screens. Prospecting with plants, on the other hand will usually involve all three interventions.

For the purposes of the initial collection of biotic samples the raw material input of biodiversity is generally a *non-rival* resource. Collection by one individual rarely impedes the ability of another potential consumer to collect the same species. However, in the case of endangered species; species of limited size; or species making it through to further stages of testing, development and production; biodiversity may prove to be *rival* due to the effects of *congestion* on the resource. The intensity of collection activities relative to the prevalence of the species may cause the quantity or quality of the remaining stock to be degraded to the point where it impairs the ability of another collector to gather the same species. *Rivalness* in the later stages of pharmaceutical prospecting may imply absolute limits on the successful development of promising new compounds and raises concerns regarding the extinction of such species. We limit our discussion to the initial provision of the *non-rival* 'raw material' input.

Non-intensive collection of biotic samples from public wildlands in developing countries is not subject to much in the way of government restriction or control. Collecting permits are required in some countries; fees payable to public authorities expressly for the privilege of collection are virtually unheard of. The difficulty and cost of asserting *exclusivity* to biological resources has left public authorities with little effective control over access to biodiversity. In this context, biodiversity is a *non-exclusive*, as well as *non-rival* resource, and fits the definition of a *public good*. As a result, biodiversity is often left in a state of *open access* and is freely collected by all comers - biodiversity is treated as a 'free good' by collectors. It is, therefore, extremely difficult for the state or an individual, firm or other societal group to capture the value of pharmaceutical prospecting that is attributable to biodiversity itself. The outcome of this *market failure* is that the actual returns to maintaining biodiversity are less than the social returns. Given these conditions, pharmaceutical prospecting provides no incentive for continued investment in the protection of biodiversity, alternative land uses appear more favorable, and land will be taken out of the production of biodiversity.

Species Information: Collection and Identification of Biotic Samples

In producing biotic samples for use in pharmaceutical R&D, a number of different types of information about species may be generated. This information often guides the selection of species for screening and includes:

- collection information - date, location, site conditions, etc.
- taxonomic classification of the organism,[6]
- ecological data indicating biochemical activity,

[6]Environmental samples are an exception. They are usually put through at least an initial screen before they are classified (Garrity, pers. comm. 1992).

- ethnobotanical information about traditional medicinal uses of plants, and
- reports of biochemical activity for a given species, genus or family.

The rest of the paper focuses on the task of generating species information in *collection and taxonomic identification activities*, which are essential inputs in pharmaceutical prospecting.

Information, or knowledge, of all kinds is *non-rival* - consumption of knowledge (learning) does not reduce the opportunity of the next consumer to learn the same information. Species information - whether taxonomic, ecological, ethnobotanical or otherwise - is no exception. However, the ability of a potential consumer to learn or acquire a particular set of information does depend on the *exclusivity* accorded to

- the knowledge already gained by another consumer
- the raw material or raw data behind the knowledge and
- the finished product generated by the application of the knowledge.

In the latter two cases, a lack of exclusivity may, respectively, enable a potential consumer to 'reinvent the wheel' or 'reverse engineer' *non-rival* information.

In theory, species information that is generated with biotic samples may be either shared publicly or closely guarded. However, free and open exchange of this information and associated biotic samples is the evolved institutional norm by which taxonomists operate. Daly (pers. comm., 1992) reports that even at a large institution such as the New York Botanical Garden roughly half of the material collected on an expedition is sent out to external experts for classification. Identification of specimens essentially works on the barter system with taxonomists working toward the shared goal of the advancement of science in the 'spirit of professional cooperation' (Townes 1992). This *non-exclusive* approach has led to a contraction in the supply of taxonomic research and expertise due to the vulnerability of the profession to changes in the level of public and philanthropic support.

Even if species information is held in a proprietary fashion - i.e. it is treated as *exclusive* - its *non-rival* nature may allow other consumers (read competitors) to 'reinvent the wheel.' The collection and identification of a biotic sample by one taxonomist does not prevent a colleague from returning to the field and generating the same information about the same species. Likewise, access to the biotic sample would allow others to 'reverse engineer' the species classification. Thus, engaging in the generation of taxonomic and collection information does not guarantee the collector the opportunity to *capture* the full value of the initial investment in information generation. In economic terms the 'market' fails to provide the requisite incentive to invest in the generation of species information

Species Information: Pharmaceutical R&D

The objective of pharmaceutical R&D into natural products is to generate the requisite amount of knowledge about a species and its chemical constituents to ascertain if any of these compounds has potential as a marketable drug. As with species information

generated during the collection stage, this information is *non-rival*. In general, those engaging in pharmaceutical R&D guard the information they generate very closely. Despite the assertion of *exclusivity* over this information, other potential consumers of this knowledge are - in theory - still able 'reinvent the wheel' or 'reverse engineer' the information through access to the original raw material or the final product.

As a result, a second pharmaceutical company could reproduce a drug developed by another company and corner the market by selling the drug at a lower price than its competitor. The second company could sell at a lower price because, presumably, it would have lower R&D costs to recoup from its product sales by virtue of having clues as to what information to generate. In this fashion, the non-rival nature of the information derived in pharmaceutical R&D conspires to reduce the returns to investments in drug innovation, leading to a less than optimal rate of drug innovation and provision of pharmaceutical products.

In the case of drugs derived from natural products the practical difficulty of generating identical information leading to the development of the same drug should not be understated. 'Reinventing the wheel' involves retracing a number of complex steps including collection of the same species and development of comparable screens that search for the same disease target. It is unclear how such a process would generate a significant cost advantage for a potential competitor. 'Reverse engineering' involves working backwards from the marketed drug to the structural determination of the chemical compound. As noted earlier, however, naturally produced compounds are often difficult to commercially synthesize. If this is the case, then 'reverse engineering' would require a company to work backward from a chemical compound to the original and *unknown* species. The ability to exclude others from the taxonomic and collection information generated earlier in the prospecting process would make this a difficult feat - akin to looking for a needle in a hay stack.

Policy Issues

Policy solutions to these incentives problems should enable individuals, firms, communal groups, institutions or governments in developing countries to capture an appropriate portion of the value of pharmaceutical prospecting. In the case of biodiversity this value should be determined by the demand for the raw material and the supply costs of biodiversity protection. In the case of species information the value should reflect the demand for the innovative end product, the marginal production costs of this end product *and* the costs of the investment made in information generation.

In order to resolve the incentives problem posed by the *non-rivalness* of information produced in pharmaceutical R&D, most developed countries have legislated intellectual property rights that provide patent protection for novel compounds.[7] In obtaining a

[7] Tyler (1979) points out that as an unfortunate consequence of the current system of intellectual property rights maintained in countries such as the U.S. and the United Kingdom, disincentives are established for research into other potentially useful areas of natural products such as multi-source drugs and compound-based drugs with a long history of use.

patent, a company gives up its *exclusivity* over the information it has generated in return for a legal guarantee of *exclusive* rights (over a set time period) to sell the product itself. Thus a company will reap monopoly profits from its investment in R&D should any of its lead compounds prove to be of commercial value.

As described above, difficulties in 'reinventing the wheel' and 'reverse engineering' information reduce the extent of the incentives problem encountered in pharmaceutical prospecting relative to that found in the case of R&D based on compounds fabricated in the laboratory. Patenting, therefore, might be less important in the case of pharmaceutical prospecting. It is unlikely that this situation would, however, justify a separate policy approach for natural product derived pharmaceuticals - particularly as advances in basic science and technology may render natural product compounds more amenable to commercial synthesis.

Solutions to the incentives problem posed by the *non-rival* and *non-exclusive* characteristics of biodiversity and species information - generated during collection and identification of biotic samples - involves either government intervention to provide these public goods or the development of means to enable the 'private' appropriation of their value. While public funding of biodiversity protection and the generation of species information has a long tradition, both budgetary limitations and the increasing commercialization of biodiversity suggest that methods for 'privatizing' these activities are worth exploring.[8] Put another way, since pharmaceutical companies are receiving monopoly profits from materials originating in biodiversity-rich developing countries, these countries must have some claim on a share of these profits.

In order to capture the value of biodiversity - the 'raw material' in pharmaceutical prospecting - developing countries are beginning to develop their capacity to *exclude* potential collectors from public wildlands. Such exclusion might involve some combination of the institution and enforcement of legal property rights over species found in public wildlands, or effective managerial control over these wildlands. If it is possible to exclude potential consumers from access to biodiversity - or some subset of species - effective control over the benefits of the resource may be assured through the institution of a system for charging potential collectors for access to the resource.[9]

Unlike the case with information, *non-rivalness* of species means little if access is not possible. Information may be recreated by 'reinventing the wheel' or 'reverse engineering,' but species cannot be regenerated if access is not permitted. The potential

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[8]See Sedjo (1992) and Simpson (1992) for theoretical overviews of contracting and property rights issues. Both authors suggest that the seemingly gradual move towards property rights over wild genetic resources in the form of legal and administrative control is driven by technological change. Improvements in biotechnologies may make the benefits of biological resources more apparent, while growing ability to identify species might lower the costs of enforcing exclusivity.

[9]A recent law passed in Costa Rica requires collectors to submit an application for a collection license that details their collection plans. If approved, non-resident foreigners are required to purchase a $30 collecting license that is valid for six months. All collectors must deposit voucher samples with the national collections and send copies of related publications to the national library.

stumbling block to this approach is the existence of pan-tropical species. Since many species are not endemic to a single country, it may prove difficult for a country to effectively exclude a collector from access to a particular species (known or unknown) that is found within its borders.

A second method for capturing the value of biodiversity protection is the establishment of contracts with local or foreign collectors for a share of any future returns from marketable uses of a species' chemical compound or semi-synthetic derivatives of the compound. The initiation of either exclusion mechanisms or contractual arrangements begin to address the incentives problem with regard to biodiversity protection because they implicitly insert the costs of biodiversity protection into the pharmaceutical prospecting process. Currently, these costs are not reflected in pharmaceutical prospecting as collectors are typically not required to purchase specimens or access rights.

In the case of species information generated during the collection and identification of a biotic sample, it may be difficult to develop mechanisms for the exclusion of potential consumers from the information or its end product. The provision of intellectual property rights over biotic samples is unlikely as they do not represent inventions *per se*. As discussed above the exclusion of other potential consumers from direct access to a collectors 'database' of information would not necessarily eliminate the *non-rivalness* problem. Other collectors could still 'reinvent the wheel' or 'reverse engineer' the information. However, what cost advantage a competitor would have in this regard is unclear.

An alternative, partial solution to this problem would be for taxonomists to begin charging fees for their services (Townes 1992). These fees should reflect not only the costs of generating biotic samples, but the costs of identification (Townes 1992). As mentioned above classification work that is 'farmed out' to other specialists is carried out for free, the cost of these activities is rarely represented in taxonomists' budgets and is not charged to third parties who purchase biotic samples, such as pharmaceutical companies. Charging fees would still permit the circulation of information; however, the generation of such information would be priced in an open and competitive market. Clearly, such an innovation might take time to implement given current attitudes and methods of 'doing business' in the systematics profession.

Collectors of biotic samples may also enter directly into contracts that access future monopoly profits of successful products or provide non-monetary benefits. Laird (1992) provides a detailed description of a number of emerging contractual arrangements between pharmaceutical companies and the suppliers of biotic samples. As these contracts are negotiated directly with pharmaceutical companies the ability of a developing country to invest in the development of the human resources necessary for collection and identification of species will allow a country to gain a large share of the returns from pharmaceutical prospecting.

In a similar vein, contractual arrangements or vertically integrated operations in which the initial stages of pharmaceutical R&D are performed in-country provide additional opportunities to capture more of the value of pharmaceutical prospecting. Developing countries wishing to capture a larger share of the value generated by pharmaceutical

prospecting should, therefore, consider investing in developing internal capabilities in pharmaceutical R&D or attracting external investment by existing pharmaceutical companies.

Finally, there may be synergies between efforts made at different stages in the pharmaceutical prospecting process. The ability on the part of a developing country to control access to its biodiversity might also serve to limit any problem posed by the *non-rivalness* of species information generated during collection and identification. Collectors that are guaranteed exclusive access to particular species are in a much better contractual negotiating position. It may also be the case that by investing in the generation of species information and striking contracts with pharmaceutical companies, a developing country may be able to capture the value attributable to its biodiversity without the need to engage in developing potentially costly mechanisms of exclusion.

In sum, there may be a number of ways that a developing country can try to capture the value of pharmaceutical prospecting. Drawing the distinction between the three stages in pharmaceutical prospecting suggests that the value of *conservation* does not lie simply in protecting, or 'saving,' biodiversity. Throughout the entire process of pharmaceutical prospecting information - and consequently value - is being added to the species under investigation. If a developing country wants to appropriate a large share of the value-added from pharmaceutical prospecting it must invest - or encourage outsiders - to invest in the generation of species information within the country.

Recognition of the distinction between biodiversity and species information suggests that the process of getting to 'know' and 'sustainably use' biodiversity are rewarding endeavors of economic merit in their own right. Indeed, as discussed in the next section, investments in biodiversity protection and species information are likely to be complementary activities. Thus, if conservation of biodiversity is to be a meaningful concept, and sustainable over the longer term, it must be understood as a *process* involving the complementary steps of 'saving, knowing and sustainably using' biodiversity (Janzen 1990; WRI 1992).

4. A Model of Biodiversity Investment Choice

Given that it is possible for a developing country to employ the methods described above to control either or both its biodiversity and species information it becomes useful to explore how developing countries should allocate scarce resources to conservation activities. The decision between, on the one hand, protecting the stock of *in situ* biodiversity, and on the other, generating species information through taxonomic work and pharmaceutical prospecting process that 'adds value' to this stock is captured below in an analytical model.

We assume that 'information-generating effort' is distinct from the effort that is involved in protecting the *in situ* biodiversity stock. 'Protection effort' consists of protected area management, maintenance and monitoring efforts, etc. - all of which are essential to production of the biochemical 'raw material' input but do not by themselves 'add value' to this input. As argued in previous sections, pharmaceutical value can only be added to

the 'raw material' input through increased in-country information-generating effort in taxonomic and pharmaceutical research and development (R&D) processes.

To make the problem interesting, we assume that scarce resources in the developing country mean that the total 'effort' that can be allocated to protection as opposed to information generation activities is fixed, thus imposing an opportunity cost on the country's decision to invest more effort in the latter activities. To simplify the analysis, we also assume that the final pharmaceutical product must compete with similar products on the international market, and thus faces a competitive price.

The process of pharmaceutical production from natural products can therefore be characterized by a production function, in which the final pharmaceutical commodity, Q, results from the extracted input of biochemical 'raw material', R, from the protected biodiversity stock and the accumulated 'knowledge', K, generated by the taxonomic and R&D effort. As in standard renewable resource (e.g. fishery) models, *effort* will be used in this model as some combination or index of the vector inputs required for either protection or information-generation activities - e.g. labour, materials, capital, etc. The production function has the following properties

$$Q = f(R, K), \tag{1}$$

where $f_R > 0$, $f_{RR} < 0$, $f_K > 0$, $f_{KK} < 0$.[10]

As noted above, R and K are products of 'protection effort', E_2, and 'information-generating effort', E_1, respectively and are determined by

$$R = h(E_2), \qquad \text{where } h' > 0,\ h'' < 0, \tag{2}$$

$$\dot{K} = g(E_1) - wK, \qquad K(0) = K_o \geq 0, \tag{3}$$

where $g' > 0$, $g'' < 0$ and w can be considered the 'rate of depreciation' of useful accumulated knowledge in the pharmaceutical value-added process. Equation (2) suggests that the supply of biochemical raw material for pharmaceutical production is a function of protection effort, and subject to diminishing returns. Equation (3) indicates that the knowledge accumulated through additional taxonomic and R&D activities is a function of the effort devoted to these information-generating activities in connection with pharmaceutical value-added. However, this knowledge can quickly become 'obsolete', so K is assumed to decay at the rate w. To simplify matters, we have not included any 'direct' costs of using effort; rather, we impose a total limit, $\hat{E}$, on the availability of effort such that

$$\hat{E} = E_1 + E_2, \qquad E_1 \geq 0,\ E_2 \geq 0. \tag{4}$$

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[10] In this model we will follow conventional notation by omitting the argument of the time-dependent variables, by representing a derivative of a function by a prime, by employing lettered subscripts to indicate partial derivatives of a function, and by denoting the time derivative of a variable by a superscript dot.

If p is the competitive price for the pharmaceutical product, i is the opportunity cost of accumulated capital (knowledge) and c is the cost of supplying raw biochemical material inputs to the process, then the discounted economic returns to the developing country of investing in pharmaceutical value added is

$$\int_0^{\infty} e^{-\delta t}\{pQ - iK - cR\}\, dt, \tag{5}$$

where δ is the social rate of discount, which also represents the returns from alternative assets in the economy.[11] We assume that the country wants to maximize (5) subject to (1)-(4) through allocating 'effort' between protection and information generation. The Hamiltonian of the above problem becomes

$$H = pf(h(E_2), K) - iK - ch(E_2) + \lambda[g(\dot{E} - E_2) - wK], \tag{6}$$

where λ is the costate variable or the shadow price of accumulated knowledge gained from information-generating activities in the pharmaceutical value added process. In the above control problem, K is a state variable and E_2 is the control variable. Assuming an interior solution, the maximum principle yields the following conditions

$$g'\lambda = (pf_R - c)h', \tag{7}$$

$$\dot{\lambda} = (\delta + w)\lambda + i - pf_K. \tag{8}$$

Equation (7) determines the optimal allocation of effort along the optimal path. It states that the marginal value to allocating effort to protection must equal the marginal value of allocating effort to information-generating activities. Equation (8) governs the change in value of knowledge gained through the latter activities. We can interpret it as stating that the net 'profit' to accumulating such knowledge is determined by the current value marginal product of that knowledge, pf_K, plus any capital gains, $\dot{\lambda}$, *less* the total opportunity costs of accumulating K, $(\delta + w)\lambda + i$.

By differentiating (7) we obtain

$$[pf_{RR}(h')^2 + pf_R h'' - ch'' + \lambda g'']\dot{E}_2 = \dot{\lambda} g'. \tag{9}$$

The long-run equilibrium can be solved by utilizing (3), (7), (8) and (9), and assuming that it occurs when protection effort, accumulated knowledge and the value of that

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[11] The distinction between i and δ needs to be clarified somewhat. Although K is considered accumulated 'knowledge' about the pharmaceutical potential of extracted biodiversity, it clearly has to be 'stored' somewhere, e.g. in laboratories, computers, researchers, etc. It will obviously cost something to maintain this research infrastructure for storing knowledge, and i represents the 'interest payment' associated with this direct cost. On the other hand, δ is the social rate of discount, which is determined both by the pure rate of social time preference and the marginal opportunity cost of capital in the economy. Effectively, it represents the economic opportunity cost for the whole pharmaceutical value added process, in that the stream of income gained from investing in this process must be weighed against other economic opportunities available to the developing country.

knowledge are all constant. Through substitutions, the equilibrium can be characterized by the following system of equations

$$(\delta + w)(pf_R - c)h' + g'i = pf_K g', \qquad \text{for} \quad \dot{E}_2 = \dot{\lambda} = 0, \tag{10}$$

$$g(\hat{E} - E_2) - wK = 0, \qquad \text{for} \quad \dot{K} = 0. \tag{11}$$

Equation (10) indicates that in the long run, the net returns in terms of pharmaceutical value added from effort allocated to protection, $(pf_R - c)h'$, must be equated with the (discounted) net returns from information-generating effort that leads to accumulated knowledge, $(pf_K - i)g'/(\delta + w)$. Equation (11) suggests that in the long run sufficient effort must be allocated to information-generating activities in order to replace knowledge about the pharmaceutical process that has become 'obsolete'.

From (10) and (11), the slopes of the curves $\dot{E}_2 = \dot{\lambda} = 0$ and $\dot{K} = 0$ can be determined in (E_2,K) space as

$$\left.\frac{dE2}{dK}\right|_{\dot{K}=0} = -\frac{w}{g'} < 0, \tag{12}$$

$$\left.\frac{dE2}{dK}\right|_{\dot{E}_2=0} = \frac{g'pf_{KK}}{\alpha} > 0, \tag{13}$$

where $\alpha = (\delta + w)[pf_{RR}(h')^2 + pf_R h'' - ch''] + [pf_K - i]g'' < 0$.[12]

Thus the curve $\dot{K} = 0$ is negatively sloped, whereas the curve $\dot{E}_2 = \dot{\lambda} = 0$ is positively sloped. As shown in Figure 1, the resulting equilibrium is a saddle point, and the saddle path is positively sloped.

The equilibrium (E_2^*, K^*) shows the optimal allocation of effort between protection of biodiversity *in situ* and 'building' up knowledge about the valuable biochemical properties of species in order to capture the long-run returns to pharmaceutical value added.

Not surprisingly, effort has to be allocated to both activities if the full 'value added' is to be gained; that is, the two type of efforts are *complements* in the long run. If the initial level of accumulated knowledge is low ($K_o < K^*$) in the developing country, then the optimal path indicates that both protection effort, E_2, and information-generating effort, E_1, must be increased. However, Figure 1 also indicates that if the initial K is low and the country allocates too much effort to protection, then the resulting path will be inefficient. Similarly, if the initial K is high ($K_o > K^*$), then the initial protection effort must also be high, and both accumulated knowledge and E_2 must be scaled down over time. If the initial K is high in the country, but too little effort is allocated to biodiversity protection, then the resulting path is sub-optimal with regard to the long-run returns to pharmaceutical value added.

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[12] Note that $[pf_K - i]$ must be greater than zero if $\dot{\lambda} = 0$ in Condition (8) for the long run equilibrium.

Comparative static analysis of the long run equilibrium can be employed to indicate the impacts of changes in the price of the final pharmaceutical product, p, the discount rate, δ, the rate of obsolescence on accumulated knowledge, w, the 'interest payments' associated with this knowledge, i, the costs of using biochemical raw material, c, and total effort, $\hat{E}$. Here, we show explicitly only the effects of changes in the product price and the discount rate, although we briefly indicate the results of the other comparative statics.

A change in p has the following impacts on the long run equilibrium

$$\frac{dK^*}{dp} = \frac{g'(f_K g' - f_R h')}{D} \begin{cases} \geq 0 & \text{if } f_K g' \geq f_R h' \\ \leq 0 & \text{if } f_K g' \leq f_R h', \end{cases} \tag{14}$$

$$\frac{dE_2^*}{dp} = -\frac{w(fKg' - fRh')}{D} \begin{cases} \geq 0 & \text{if } f_R h' \geq f_K g' \\ \leq 0 & \text{if } f_R h' \leq f_K g', \end{cases} \tag{15}$$

where D is the determinant of the Jacobian matrix for the comparative static solution of the long run system (10) and (11), with $D = \alpha w - (g')^2 p f_{KK} > 0$.

Clearly, the relative marginal productivity of protection as opposed to information-generating effort in terms of pharmaceutical value added will determine which input is increased if the product price rises. If the marginal productivity of E_1 is relatively higher, then in response to the price rise more effort should go into this activity, and thus the accumulation of knowledge, and less into protection of *in situ* biodiversity. If the marginal productivity of E_2 is relatively higher, the opposite is the case.

An increase in the discount rate, δ, has the following impacts on the long run equilibrium

$$\frac{dK^*}{d\delta} = -\frac{g'(pfR - c)h'}{D} < 0 \tag{16}$$

$$\frac{dE_2^*}{d\delta} = \frac{w(pf_R - c)h'}{D} > 0. \tag{17}$$

A rise in δ will lead to an increase in the equilibrium level of protection effort and a fall in K*. Effectively, this implies that the developing country finds the long run returns to the pharmaceutical value added process to be a less attractive economic proposition, and is less willing to 'tie up' as many economic resources in accumulating knowledge for use in this process over the long term.

The comparative static effects of increases in the 'interest' cost associated with K and the costs of the input R are fairly straightforward. An increase in i causes a re-allocation of effort in the long run away from information generation, and thus knowledge accumulation, and to more *in situ* protection; whereas an increase in c leads to the opposite result. Increases in w and in $\hat{E}$ both result in a fall in equilibrium K, but the effect on E_2 is less certain.

5. Conclusion

Should a developing country invest more in taxonomic and R&D efforts in order to accumulate more knowledge about the use of natural products in developing new pharmaceuticals, or should greater effort by allocated to protection of the *in situ* biodiversity stock that is the source of the biological 'raw material' in the first instance?

In this paper, we have suggested that an important issue that needs to be addressed *a priori* to this allocation decision is the ability of a developing country to find solutions to the *incentives* problem posed by the *non-rival* and *non-exclusive* characteristics of biodiversity and species information. Fundamental to any such solution is recognition of the distinction between biodiversity and species information. That is, simply 'saving' or protecting a country's stock of biodiversity is not in itself sufficient for 'capturing' pharmaceutical value. Throughout the entire process of pharmaceutical prospecting information - and consequently value - is being added to the species under investigation. If a developing country wants to appropriate a large share of the value-added from pharmaceutical prospecting it must invest - or encourage outsiders - to invest in the generation of species information within the country.

In addition, before investing in the pharmaceutical value added process, the country must determine whether there is a potential economic return to be made from allocating *any* resources to this process. Resources are scarce in developing countries, and it is not at all obvious that the returns from capturing the full pharmaceutical value of biodiversity is worth the costs of this enterprise for all countries. Thus careful consideration of the *incentives* problem and of the economic returns to investing in the pharmaceutical value added process is an essential pre-condition before allocating resources to this effort.

If this pre-condition is met, then the issue of how best to allocate effort between biodiversity protection and information-generating activities becomes crucial. The model of this paper has confirmed that both activities are complementary to the pharmaceutical value added process, but there is always a danger of combining 'too much' protection effort with 'too little' taxonomic and R&D effort, and *vice versa*. The crucial determinant of the optimal allocation of effort between these activities is their relative marginal productivity in the pharmaceutical prospecting process over the long term, particularly in the face of changes in the pharmaceutical product price, the discount rate and other parameters. However, in order for developing countries to maximize the potential returns from capturing the pharmaceutical value of their *in situ* biodiversity it is important for future research to clearly distinguish between the value added of the 'information' input and that of the 'raw material' input.

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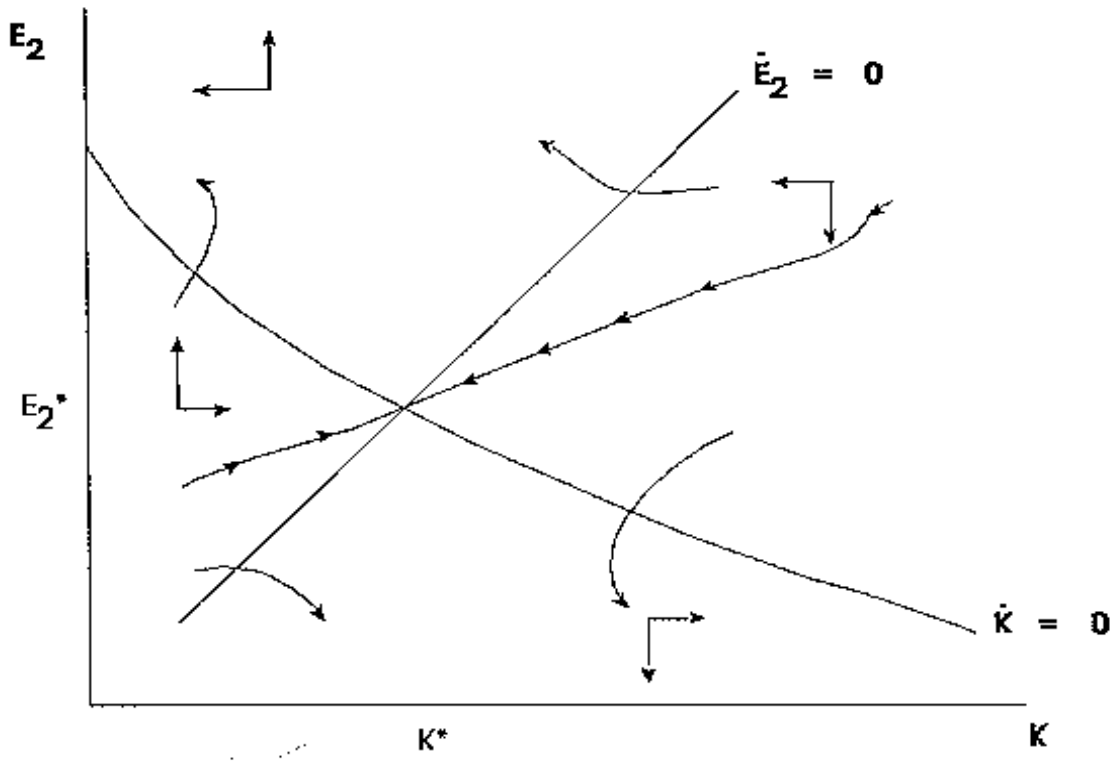
Figure 1 Optimal Allocation of Conservation and Information-Generating Effort



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David W. Pearce, Anil Markandya and Edward B. Barbier

Blueprint for a Green Economy, Earthscan, London, 1989 (paperback £8.95)

This book was initially prepared as a report to the Department of Environment, as part of the response by the government of the United Kingdom to the Brundtland Report, *Our Common Future*. The government stated that: '...the UK fully intends to continue building on this approach (environmental improvement) and further to develop policies consistent with the concept of sustainable development.' The book attempts to assist that process.

Edward B. Barbier, Joanne C. Burgess, Timothy M. Swanson and David W. Pearce

Elephants, Economics and Ivory, Earthscan, London, 1990 (paperback £10.95)

The dramatic decline in elephant numbers in most of Africa has been largely attributed to the illegal harvesting of ivory. The recent decision to ban all trade in ivory is intended to save the elephant. This book examines the ivory trade, its regulation and its implications for elephant management from an economic perspective. The authors' preferred option is for a very limited trade in ivory, designed to maintain the incentive for sustainable management in the southern African countries and to encourage other countries to follow suit.

Gordon R. Conway and Edward B. Barbier

After the Green Revolution: Sustainable Agriculture for Development, Earthscan Pub. Ltd., London, 1990 (paperback £10.95)

The Green Revolution has successfully improved agricultural productivity in many parts of the developing world. But these successes may be limited to specific favourable agro-ecological and economic conditions. This book discusses how more sustainable and equitable forms of agricultural development need to be promoted. The key is developing appropriate techniques and participatory approaches at the local level, advocating complementary policy reforms at the national level and working within the constraints imposed by the international economic system.

David W. Pearce, Edward B. Barbier and Anil Markandya

Sustainable Development: Economics and Environment in the Third World, London and Earthscan Pub. Ltd., London, 1990 (paperback £11.95)

The authors elaborate on the concept of sustainable development and illustrate how environmental economics can be applied to the developing world. Beginning with an overview of the concept of sustainable development, the authors indicate its implications for discounting and economic appraisal. Case studies on natural resource economics and management issues are drawn from Indonesia, Sudan, Botswana, Nepal and the Amazon.

David W. Pearce and R. Kerry Turner

** ***Economics of Natural Resources and the Environment,*** Harvester-Wheatsheaf, London, 1990.

This textbook covers the elements of environmental economics in theory and in application. It is aimed at undergraduates and includes chapters on sustainable development, environmental ethics, pollution taxes and permits, environmental policy in the West and East, recycling, and optimal resource use.

David W. Pearce, Edward B. Barbier, Anil Markandya, Scott Barrett, R. Kerry Turner and Timothy M. Swanson

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